



Applying life cycle inventory to reverse supply chains: a case study of lead recovery from batteries

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Abstract

The increasing demand for efficient management of used products after the end of their life cycle stems from the increasing awareness of modern society about possible threats against the environment. Used starter or lead–acid batteries contain lead up to 65%, which is also valuable after the end of their life cycle. Recycling of lead gives rise to some environmental problems associated with its collection, processing and recycling and, finally, entering the main (forward) supply chain. In this paper, the lead recovery from old batteries is examined using life cycle inventory analysis (LCIA). The reverse supply chain of used starter or lead–acid batteries is outlined and analyzed. A model for this product system is formulated, which is used to identify the lead emissions as well as all the environmental exchanges through materials balance. The proposed model formulation, which is appropriately adapted to the needs of the reverse supply chain, is used as a tool in a LCIA in order to identify those stages in the battery life cycle that give rise to the greatest environmental burdens. A similar analysis is also made for the case of disposal. The model may be used in order to assess all the associated impacts in an in-depth life cycle analysis (LCA). A preliminary comparison between the two end-of-life scenarios in terms of their environmental inputs and outputs is also attempted. Thus, based on several assumptions, an inventory analysis referring to the above chains has been conducted whose results have been summarized in an Inventory table, which produces comprehensive information about each life stage of the examined end-of-life scenarios.

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Keywords: Lead–acid batteries; Life cycle inventory analysis; Materials balance; Recycling; End-of-life scenarios; Reverse supply chain; Disposal chain

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1. Introduction

1.1. General

Recovery of used products after the end of their life cycle is a means for environmental protection and a source of business profit through their exploitation. Reverse logistics (Fleischmann et al., 1997; Giudini, 1996), in particular, aims at improving the exploitation of used products, or their parts, through recycling, remanufacturing or other forms of recovery (Ayres, 1995). The new activities of existing companies or the new production systems (e.g. recycling units) created have generated new markets (including electronic commerce) and have led to significant reduction of the environmental degradation (Lee et al., 1995).

Evaluation of the latter may be effected by using life cycle analysis (LCA), which has been applied mainly for the measurement of environmental impacts associated with new products from ‘cradle to grave’ (NORD, 1995; SETAC, 1991, 1993). In fact, little attention has been paid to the application of this technique to product recovery. This paper reports results from research focusing on this subject, that is, application of LCA (particularly life cycle inventory analysis (LCIA)) to reverse logistics activities such as collection, recycling and redistribution. Thus, conclusions may be drawn as to the environmental effectiveness of current recovery practices applied to these products.

The literature related to LCA and environmental implications of logistics activities taking place in upstream or downstream stages of lead–acid batteries used in vehicles (compatible, electrical or hybrid) focuses on listing mainly lead releases during the above logistics activities and analyzing the environmental consequences attributed to primary or secondary lead. In particular, a small number of LCA studies have aimed at analyzing the environmental burdens associated with both forward and reverse logistics activities. They mainly focus on the environmental implications of lead releases arising from logistics activities of the batteries upstream stages, while also including some downstream stages referring to lead recovery.

Lave et al. (1995) first examine the current and near term life cycle consequences of producing and reprocessing lead–acid batteries used to power electric cars. So, they measure the lead releases to the environment from production and recycling concluding that mining, smelting and recycling activities more than 500 kg of batteries per vehicle would result in lead releases 80 times greater per vehicle mile than a gasoline powered vehicle with a current starter battery. Lave et al. (1996) examine the effects of current technology of battery powered vehicles on urban ozone and lead discharges and also the quantity of lead that could be discharged into the environment as a result of lead-based battery powered vehicles. Finally, they estimate that, by 1998, lead–acid battery powered vehicles would be a potential environmental liability compared with the new ultra-low emission of gasoline powered vehicles.

Another attempt at analyzing the recovery of used batteries (lead–acid starting lighting ignition batteries SLI batteries) with the help of LCA has been made by Robertson et al. (1997). They show how the technique of in-depth LCA,

appropriately adapted to the needs of the industry, could be used as an internal design and assessment tool to identify those stages in the battery life cycle that give rise to the greatest environmental burdens, and to assess the effects of changes in the cycle to those burdens. In this paper, only the first stage of the reverse supply chain, that is, collection/transportation related activities, are examined, especially the transportation of used batteries on battery-breaking plants located in England. In particular, a comparative analysis between different transportation scenarios is examined in order to uncover the possible environmental gains depending on the choice of the respective scenarios. The study is conducted by aggregating inventory data into categories according to their potential environmental impact leading in useful conclusions in terms of alternative transportation scenarios.

Socolow and Thomas (1997) examine the key criteria that an ideal lead-battery recycling system must meet, such as maximal recovery of batteries after use, minimal export of used batteries to countries where environmental controls are weak, minimal impact on the health of communities near lead-processing facilities, and maximal worker protection from lead exposure in these facilities. In their paper, attention is paid mainly to the batteries of electric and hybrid vehicles and the use of lead as gasoline additive, and the focus is on the environmental and health impacts, which results during lead recycling. They conclude that the goal of better environmental protection from lead discharges should be clean recycling.

In the paper of Steele and Alien (1998) a comparison of potential health and environmental impacts of four battery technologies, focusing on recycling and waste disposal life stages takes place, while emphasis is given to the design factors that could prevent or increase impacts. For this comparison, they have used an abridged LCA (Graedel et al., 1995), which produces easily comprehended information about each life stage of a product in order to analyze the environmental impacts (using mainly inventory data) associated with the mentioned stages.

Rydh (1999) has evaluated the environmental impact of both, the vanadium redox battery (vanadium battery) and the lead–acid battery, for use in stationary applications using an LCA approach. In this study, the calculated environmental impact was lower for the vanadium battery than for the lead–acid one. The total environmental impact for both types of battery is evaluated with the environmental priority strategies (EPS) and the Environmental Theme (ET-long-term goals) methods.

Finally, in the paper of Karlsson (1999) detailed treatment of the releases of lead in various stages of the lead–acid battery product cycle is given. This study focuses on the lead releases in the forward supply chain as well as during recycling. The analysis shows that the losses from the production and recycling processes are so low that consumption losses and the recovery rate dominate the total system losses. It is also shown that, in a steady state with very high recovery of used batteries, the system losses are small compared with natural lead flows and to historical losses during industrialization.

2. Recycling batteries

2.1. Batteries and lead

Lead is a non-ferrous metal, which may be, used in soil pipes, accumulators (alloy with antimony), as antiknock in gasoline (tetraethyl lead $\text{Pb}(\text{C}_2\text{H}_5)_4$), cable sheathings, paints and different alloys (white metal, pellets, types, etc.). Although the main uses of lead have decreased as a result of substitution in cables by plastic or exclusion of use of tetraethyl lead in vehicles, the increase of the number of automobiles and the expansion of the construction sector as well as the extension of communications (cables) have created new perspectives (Pugh and Breeze, 1995; World Mining and Metals Yearbook, 1996).

In contrast to other non-ferrous metals, lead is recoverable from nearly all fields of application, except for chemical uses. Apart from separation and preparation problems in some sectors of minor importance, recycling also meets some difficulties in collection. Lead can be easily re-melted. Its recycling is performed mainly from scrap during the production process as well as from articles returned as waste at the end of their period of use (Wilson, 1993). The useful life cycle of these articles can be short (e.g. batteries) but some of them have a considerably longer average life cycle (e.g. cables).

By far the biggest use of lead, worldwide, is for the lead–acid battery. Lead is particularly suitable for batteries, because of its characteristics (conductivity, resistance to corrosion and the special reversible reaction between lead oxide and sulfuric acid). The majority of lead–acid batteries are used as SLI batteries (starting, lightning and ignition) for the purpose of starting the engines of cars and lorries. Another sort of lead–acid battery is the traction (driving) battery, used to power electric vehicles such as milk floats, forklift trucks and airport support vehicles. This type of battery provides the best service for ‘stop and start’ conditions. A last sort of lead–acid battery concerns stationary battery, which provides uninterrupted electrical power (e.g. in hospitals, telephone exchanges, companies, etc.)

The main components of a lead–acid battery and, more specifically, of an SLI battery are:

- active mass or lead paste which includes:
 - cathode (positive pole) which consists of metallic lead (Pb),
 - anode (negative pole) which consists of lead oxides (PbO_2),
- grids and connecting bridges made of suitable lead–antimony, lead–calcium (tin) (aluminum) alloys with additives, in negligible quantities, such as copper, arsenic, tin and selenium,
- electrolyte (liquid filling of sulfuric acid) in which lead–antimony plates are immersed,
- casing, usually made of polypropylene, and, less frequently, of hard rubber, ebonite, bakelite etc.
- other components such as paper, rubber, fiberglass and wood [Table 1](#).

Recycling is important for waste management, because it generally saves money, resources and energy. It can also be less damaging to the environment. Lead is recycled because it is easy to collect and requires less energy than extracting primary metal from its ore. However, recycling of lead gives rise to some environmental problems, mainly air pollution due to the emission of sulfur dioxide and chloridized fumes and lead discharges (Lave et al., 1996). Furthermore, the environmental impacts resulting from discharges of lead and sulfuric acid in receiving waters or in soil are important, something which is reflected in the upper limits set by several relevant directives.

2.2. *Recycling of batteries in Greece*

The secondary production of lead begins with the recovery of old scrap from worn-out, damaged or obsolete products and new scrap that is made of product wastes and smelter-refinery drosses, residues, and slag. The chief source of old scrap in Greece is lead–acid batteries, though cable coverings, pipe, sheet, and terne bearing metals also serve as a source of scrap. While some secondary lead is recovered directly for specialty products like babbitt metal, solder, re-melt, and copper-base alloys, about 97% of secondary lead is recovered at secondary lead smelters and refineries as either soft (unalloyed) or antimonial lead, most of which is recycled directly back into the manufacture of new products containing lead.

Different techniques of re-treatment and recycling may be applied for material recovery from used products. The choice of these techniques is mainly related to the product's material composition. Batteries belong to the category of products which, even when they have reached the end of their life cycle, are still valuable. This happens because the basic components of a battery are plastic and lead, which can be recycled. In the case of batteries, the recovery techniques maybe divided into:

- I) direct methods, which can re-treat batteries in the as-received condition,
- II) semi-direct methods, which treat batteries after the removal of casing,
- III) indirect methods, in which batteries are shredded or crushed and the different lead bearing components are separated from other components in a mechanical dressing stage so the lead bearing components can be smelted separately, whereas non-metallic can be disposed of as waste or resold (Vaschetti and Civera, 1997).

At the end of 1995, the secondary lead industry, consisting of ten small size companies that implement mostly semi-direct methods and melting technology for the remaining parts of batteries in furnaces of type CUPOLA or rotary furnaces. The basic problems encountered are the environmental ones, high-energy consumption and great losses of lead during smelting. However, there are two medium size companies that operate battery breakers-smelters (indirect methods) with capacities between 6000 and 10 000 metric tons per year.

To meet the need for larger quantities of secondary lead severe environmental controls (Socolow and Thomas, 1997) are necessary. Such controls aim at achieving

the best protection from the environmental consequences arising from lead-processing facilities (minimal impact on the health of communities near lead-processing facilities, maximal worker protection from lead exposure in these facilities, etc.) and, finally, at satisfying the environmental regulations imposed. The environmental key criteria that must be met by secondary lead producers concern (Phillips and Lim, 1998):

- Effluent treatment plant: electrolyte from the lead–acid batteries and wastewater from the process area must be treated using chemicals and flocculent. Metals such as lead, cadmium, copper, iron and tin should be all collected in the filtered sludge and recycled to the furnace for metal recovery.
- Gas cleaning plant: the gas from the smelting furnace must be cooled (e.g. using atomizing water sprays) before entering the baghouse filter unit. The baghouse must use high performance bags for removal of lead fume in the pulse-jet baghouse and this will be collected for recycling back to the furnace.
- Flue gas desulfurizing: sulfur dioxide from the smelting of paste must be removed in order to meet the Air Quality Guidelines. By this process gypsum is produced, which can be collected and pumped to a filtering plant where it will be dehydrated, dried and then trucked to customers to make cement and wallboard.
- Solid wastes: all steel, pallets and other wastes should be forwarded in the furnaces for recovery of the iron and for fuel. The only waste from the entire site should be a small amount of non-recyclable PVC separators that can safely be landfilled.
- Lead controls: a number of best practices must be implemented, which will prevent lead migration from lead processing facilities, and will control lead in employee blood levels.

Greek companies of secondary lead production need to adjust to most of the above-mentioned environmental controls in order to meet the demands of society for a clean environment. Several of the above environmental key criteria are not fulfilled, especially the processing of waterborne emissions or lead paste desulfurizing, due to high costs of installation, maintenance and operation. Additionally, much more efforts should be made in terms of lead controls, as Greek companies seem to lag considerably behind some other European countries. All the above reasons explain why an analysis of the reverse supply chain of lead–acid batteries is needed in order to identify as close to reality as possible its potential environmental implications.

The work presented in this paper is based on data from one of the above two medium size companies, which is a private enterprise and whose main activity is lead recycling, which is extracted mainly from batteries or, in small percentage, from leaden conduits. This enterprise is located in Aspropirgos, about 20 km from Athens.

The suppliers of used batteries appear in Fig. 1. The recycling unit processes about 21 000 tons of used batteries per year and this quantity corresponds to 25–30% of the total volume of the batteries recycled in Greece (Fig. 2). There is one more recycling

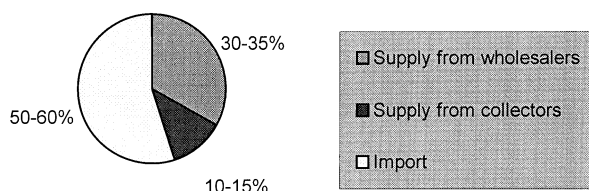


Fig. 1. Suppliers of used batteries.

Table 1
Typical composition of a battery

Components of battery	%
Active mass (PbO_x , PbSO_4)	38.5
Acid ($\text{H}_2\text{O} + \text{H}_2\text{SO}_4$)	20.0
Lead metal	27.7
Grips	1.4
Separators	4.9
Case	7.5

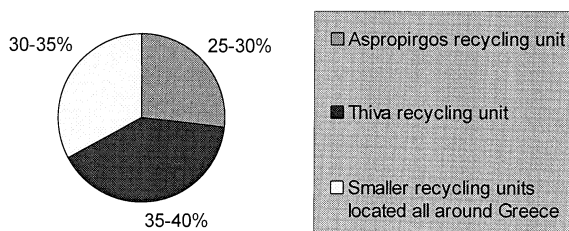


Fig. 2. Share of recycling units in Greece in total production of lead.

unit of the same capacity located in Thiva (central Greece) and many smaller units located in different locations in Greece.

Out of 100 kg of used battery, about 35 kg of lead and 7.5 kg of plastic can be recovered, therefore, about 7200 tons of lead and 2160 tons of plastic may be produced every year. There are some other products except from battery, which are made of lead (e.g. conduits), that are recycled in the unit but in no significant quantities. The plastic produced in the unit is forwarded to Greek consumers for various uses. About 90% of the lead produced in the unit is exported used for the production of pellets and lead alloys. The lead forwarded to domestic consumers is used for the production of lead sheet and conduits (see Fig. 3). There are some periods where the lead produced is stored for later use and this depends on the quality and the price of lead in the market.

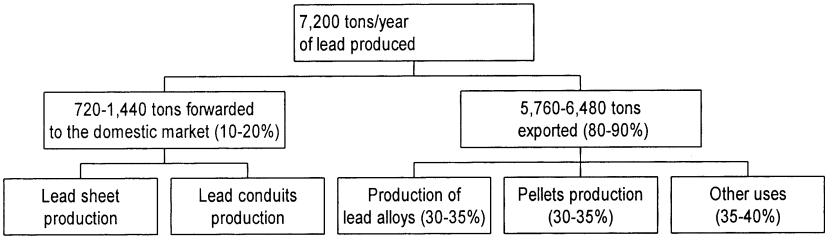


Fig. 3. Uses of lead produced by the recycling unit.

2.3. The Greek case study of the battery reverse supply chain

For the exploitation of used batteries, a reverse supply chain has been developed in the above unit, which includes all the stages of the reverse flow of the batteries, from their collection after the end of their life cycle to the production and sale of the materials produced during the recycling procedure. Several agents participate in this chain.

The stages of the chain of used batteries appear in Fig. 4. At the beginning, the batteries are usually deposited at a car electrician's shop, where cars are brought for battery replacement. Used batteries are delivered at no cost. In some cases an individual may himself replace the used battery. This means that most of the used batteries enter the reverse flow chain instead of ending up in a landfill. The batteries containing their liquids are stored in columns in the electrician's shop. Imported batteries have no liquids, because of the international legislation restrictions on transportation.

Used batteries are bought by collectors. Car electrician's shops may supply any collector demanding used batteries, but usually each such shop supplies a few collectors. The quantity of batteries a shop handles varies from a few dozens to several hundreds per year. While the batteries are stored at the shop no significant damage, deterioration or value reduction happens.

The collectors collect the batteries and transfer them using pick-up trucks. Very often collectors collect other materials as well, like iron and used igniters. As soon as the truck is full to its capacity, the collector forwards the batteries to wholesalers trading in used materials. Sometimes the collector forwards the batteries directly to the recycling unit. Collectors do not store batteries.

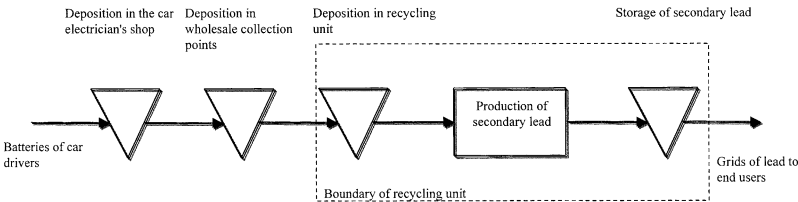


Fig. 4. The batteries reverse supply chain.

Wholesalers store used batteries for some time in yards, together with other used materials (brass, iron, aluminum etc.), and then they forward to the recycling unit.

2.4. The recycling unit

In the recycling unit processing of the product takes place. The batteries are transferred to the unit with trucks. The batteries are unloaded next to the breaker (see Fig. 5). After that, the batteries are loaded to the breaker, using a small lifting machine. The casing of some truck batteries is made of bakelite. Such batteries are broken manually and their lead is pushed to the next stages of the production process, while the bakelite is transferred to a landfill. During breakage lead oxides, plastic, paper and battery liquids are extracted. These materials have different specific weight and this makes their sorting, in a vessel full of water, easier. The lead oxides and plastic are further processed in the unit but the paper is disposed of as waste.

Lead oxides are stored next to the vessel of water and are wet. For this reason they remain outdoor until they get dry and then they are forwarded to the furnace for the remaining processes. The furnace operates on a yearly basis, 24 h a day. The operation temperature is about 1000 °C. In the furnace, apart from the lead oxide, some ancillary materials are also inserted. These materials are soda (5%), ferrous chips (6.5%), salt (2.5%) and carbon (5%). Pure lead is produced in fluid form. Byproducts are slag (in fluid form also) ashes and air pollutants (SO₂ and particulates). The fluid products, which are mixed, may get separated by allowing the mixture to flow. Lead flows first, because of its specific weight. Slag is sometimes placed in the furnace again because there is some lead remaining in it. Pure lead is placed in moulds (3000 kg) and is subject to quality control using a sampling method. After that, pure lead is driven outdoor and is cut into smaller pieces. Then, it is stored in columns until its sale.

Near to the furnace, an air pollution control system operates. Using this system the polluted air is driven to filters, where the undesirable emissions are captured and removed.

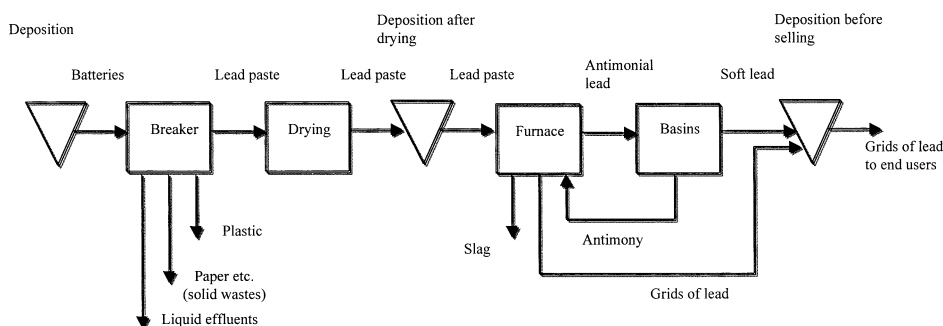


Fig. 5. Processing of batteries in the recycling unit.

The unit employs 16 persons and operates 6 days per week in two shifts, except from the furnace, which operates non-stop.

3. Life cycle analysis of the batteries reverse supply chain

3.1. Goal and scope definition

The intention of this paper is to analyze the batteries reverse supply chain and to inventory all the environmental exchanges associated with the logistics activities involved. Due to important environmental problems encountered in the course of reverse channel activities, particularly within lead-processing facilities, it is of high interest to study and analyze systematically the impacts associated with it. However, impact assessment of such a product system with emphasis on lead is difficult. So, a comparison between reverse supply chain and disposal chain of batteries based on inventory data is made in order to identify the potential shortcomings of these end-of-life scenarios. It is noted that the stages of battery material extraction and manufacturing (included in the forward supply chain) have not been considered, due to lack of adequate and/or reliable data concerning lead mines and batteries fabricators in Greece. This study may support a logistics designer in his task of designing the logistics activities or facilities included in the batteries reverse supply chain, particularly by taking into consideration also the environmental dimension.

As our study concerns the comparison of two end-of-life scenarios, the subject of the assessment is the service provided to the user or the function, which a given product has. So, this service (functional unit) must be defined and quantified. The functional unit is based on the performance of the product as specified in its standard use. In this paper the product examined concerns the used battery and, more particularly, the lead contained in it. We define 1 ton of lead as the functional unit.

An important task in the preliminary phase of LCA concerns the selection of the reference product and reference data. The first one is the general representative of the product considered, which is selected in order to define the functional unit; the second one represents the selected processes or parts of the life cycle for the reference product.

Identification of the environmentally significant processes in the examined end-of-life scenarios is of high interest for the goal of this study. First of all, definition of the system boundaries on the basis either of the selected processes and life cycle stages or the selected geographical boundaries of the product system, must take place. This definition has a dramatic impact on the results of inventory analysis.

Reverse supply chain of batteries includes the life cycle stages of collection, disaggregation and remanufacturing (both of them being part of secondary lead-processing facilities), distribution and, finally, the reuse stage. Disposal chain includes the life cycle stages of collection and landfilling.

Some important points for the simplification of the study have been taken into consideration. These concern the transportation process, which, takes place in two

stages of the reverse supply chain, namely, at the collection stage (transportation of used batteries), and at the distribution stage (distribution of the final products), that is, lead grids to the end users. It is also appeared in the collection stage of disposal chain.

By using of various approaches (cut-off methods or 5% rule), some less important processes at the processing stage have been ignored. This assumption does not influence the results significantly. More specifically, it has been assumed that storage of the ancillary materials and all the material movements in the processing unit cause negligible environmental effects (negligible emissions and minimal energy consumption).

Exclusion of the reuse stage of the final products of the batteries reverse supply chain was imperative due to lack of reliable data in terms of undetermined secondary lead uses (Fig. 3).

An important issue regarding the system's boundaries is the effect of the choice of geographical borders of a system (Lindfors et al., 1995a,b). These geographical borders may be local, municipal, national, communal, natural boundaries etc. Within different borders, different traditions, policies and laws can be applied. In the case we are examining, a significant percentage of used batteries are imported from countries where the environmental legislation may not harmonize with this of the EU. This entails possible damages for the environment due to the toxicity of batteries depending on the transportation mode.

Definition of the time horizon would be necessary when the time validity of the results, the comparison of the technology level or the time horizon, under which the environmental impact is valid, should be seen. As long as this study focuses mainly on inventory analysis, a time horizon does not need to be defined for the implementation of this LCA study.

In our study, allocation of the environmental exchanges is excluded as long as the examined end-of-life scenarios focus on a single service (as is the production of secondary lead).

4. Inventory analysis

4.1. Methodology

Inventory analysis (ISO 14041, 1998) is perhaps the most important stage of LCA (Wenzel and Hauschild, 1998; Hauschild and Wenzel, 1998). The performance of this phase is essential for the realization of the next phases of LCA, i.e. impact assessment (ISO 14042, 2000) and interpretation (ISO 14043, 2000).

Inventory begins with a flow diagram and process tree, where all the relevant processes and stages of the predefined system are outlined. A basic condition for the definition of the environmental impacts of the system is its division into subsystems (stages) linked to each other by balanced materials flows (SETAC, 1991). The system is divided in subsystems, which are described using the data for the materials and energy entering it and the products and wastes produced. When this information has

been assembled for all subsystems, the performance of the overall system may be estimated by establishing mass balances among all the subsystems.

Aggregation of data is of primary importance in this stage of LCA. Case specific data are preferable. Some basic issues in inventory analysis concern the data sources (private vs. public), the choice between use of average versus case-specific data, the kind of measurements (internal vs. external), the specification of data (publicity, age and frequency of data, changes of technology) and, finally, data availability (Miettinen and Hamalainen, 1997; SETAC, 1991).

An important step at this phase is to enact the criteria aiming at discrimination of data categories (e.g. solid wastes, energy consumption etc.). Determination of data categories is essentially the first step of the inventory analysis. These categories concern the environmental impacts (air pollution, energy consumption, etc.). The term ‘environmental impact’ is defined by scores describing the above impact categories. Each score measures the performance in relation to some criteria, which are described by particular indicators. Similarly, these indicators include some sub-indicators. ‘Criteria’ are the effects that incur relevant environmental impacts (e.g. air emissions). The indicators describe quantitatively a criterion as precisely as possible. Indicators may be described by sub-indicators (Hanssen et al., 1994; NORD, 1995).

The next step concerns the modeling of the system, where calculation of mass and energy entering or exiting in every stage of the system takes place. In particular, mass and energy balances for each stage of the system are examined (SETAC, 1991), from where total balances would incur in order to evaluate the total environmental impact of a product.

Finally, all the inputs and outputs of the system concerning mass or energy are listed in the inventory table. This table is the eco profile of the process examined.

4.2. Modeling of the batteries reverse supply chain

A schematic presentation of the stages of the batteries reverse chain, appropriate for inventory analysis, is presented in Fig. 6, which is based on Fig. 4. In particular, the stages included are:

- **Collection:** The reverse chain starts with the collection of used batteries, which are stocked at several points (mainly car electrician’s shops). Collection concerns the raw material (used battery), which is required for the stage of processing. Then, transportation of used batteries takes place, either directly from the collection points or from intermediate recovery and storage facilities to the processing (recycling) unit.
- **Disaggregation:** In this stage, which is part of the processing stage, the disaggregation of different types of batteries. This activity includes removal of the rubber casing, which is either recycled or disposed, and recovery of the components containing lead.

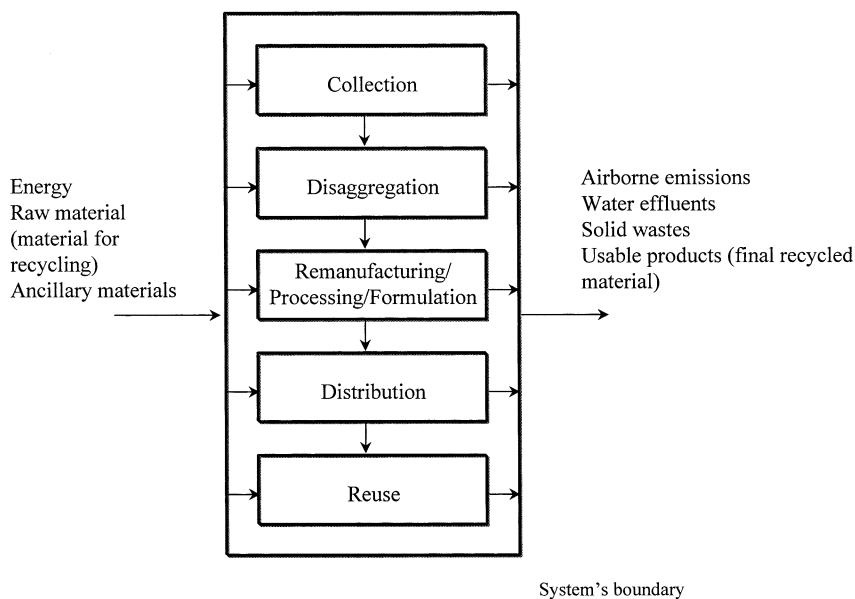


Fig. 6. Stages of inventory analysis in batteries reverse supply chain.

- **Remanufacturing/processing/formation:** This stage is supplied with the raw material (used batteries) and the ancillary materials (soda, etc.) required for the formation of the final products (grids).
- **Distribution:** These activities take place in almost any stage of the reverse chain. Transportation is defined as any movement of material or energy between operations at different locations and it takes place in any stage of the life cycle of the used product. Distribution is defined as any non-transportation activity intended to facilitate the transfer of recycled products (secondary lead) from their final manufacturer to their ultimate user.
- **Reuse:** It concerns the life cycle of the recycled product after its distribution to the users (manufacturers of new products).

An assumption made regarding the inventory analysis concerns the implementation of the conservation law of mass. It is supposed that the total mass of lead entering the system, mainly contained in used batteries, is equal to the mass leaving the system in the form of grids (product), slag or dust of lead. More specifically, it is supposed that, at any stage, the recovery of metal lead, which is enhanced by chemical reactions, is not associated with any significant change of mass of lead produced due to the addition of ancillary materials. Similarly, it is supposed that during transportation, either after the collection of used batteries or at the stage of distribution of recycled lead to the end users, no increase or reduction of the mass of lead is incurred. The same assumption holds for the ancillary materials.

Based on the above assumptions and using the symbols appearing in Fig. 7, we have the following:

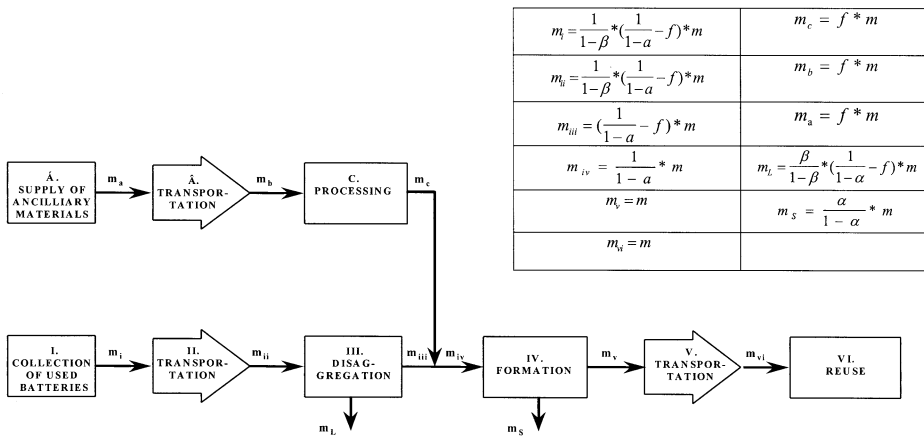


Fig. 7. Mass balance in the batteries reverse chain.

Let m be the mass of lead to be reused by the end user (producer of cables, pellets, batteries, etc.), i.e. $m_{vi} = m$. Due to the law of mass conservation, it is;

$$m_{vi} = m_v = m \quad (1)$$

During the formation stage, a loss of mass can be detected due to the production of a particular quantity of slag. Let α be the percentage of slag, which corresponds to the amount of net metal lead produced. Then:

$$\begin{aligned}
 m_v &= (1-a)m_{iv} \Rightarrow m_{iv} = \frac{1}{1-a} m_v = \frac{1}{1-a} m \\
 m_v &= m_{iv} - m_s \Rightarrow m_s = \frac{\alpha}{1-a} m_v = \frac{\alpha}{1-a} m
 \end{aligned} \quad (2)$$

where m_s expresses the quantity of slag leaving the system. We also have:

$$m_{iv} = m_{iii} + m_c \Rightarrow m_{iii} = m_{iv} - m_c \quad (3)$$

From Eqs. (1)–(3) we have:

$$m_{iii} = \frac{1}{1-a} m_v - m_c$$

As there is no change in mass of the ancillary materials at their procurement and transportation phases, it is $m_a = m_b = m_c$. If f is the percentage of the ancillary materials required for the production of lead mass m then:

$$m_c = fm_v = fm \quad (4)$$

From Eqs. (4) and (3) we have:

$$m_{\text{iii}} = \frac{1}{1-a} m - fm = \left(\frac{1}{1-a} - f \right) m$$

It is also supposed that, during the disaggregation stage, a loss of mass of lead takes place, either through the drainage system or during lead drying. If β is the percentage of lead emitted to the ecosystem in the vicinity of the plant, then:

$$m_{\text{iii}} = (1 - \beta)m_{\text{ii}} \quad (5)$$

Applying the law of mass conservation to the distribution of lead recovered, we have $m_i = m_{\text{ii}}$. Therefore:

$$m_i = m_{\text{ii}} = \frac{1}{1-\beta} m_{\text{iii}} \quad (6)$$

$$m_L = \frac{\beta}{1-\beta} \left\{ \frac{1}{1-a} - f \right\} m \quad (7)$$

where m_L expresses the quantity of lead which enters the ecosystem in the vicinity of the plant.

From Eqs. (6)–(8) we have:

$$m_i = m_{\text{ii}} = \frac{1}{1-\beta} \left\{ \frac{1}{1-a} - f \right\} m \quad (8)$$

The above equations describing the mass balances at different stages of the chain are summarized in Fig. 7.

4.3. Energy consumption

The total energy consumed in the system is the sum of energy consumed at every system's stage. Thus:

$$E_{\text{TOT}} = E_i + E_{\text{ii}} + E_{\text{iii}} + E_{\text{iv}} + E_v + E_{\text{vi}} + E_a + E_b + E_c \quad (9)$$

The energy consumed at each stage is the product of the specific energy and the mass leaving it. The specific energy u_j is defined as the energy consumed per unit of mass. Therefore:

$$E_j = u_j m_j \quad (10)$$

with $j = i, \text{ii}, \text{iii}, \text{iv}, v, \text{vi}, a, b, c$. E_j is expressed in MJ, u_j in MJ/ton and m_j in tons.

From Eqs. (9) and (10) we conclude that:

$$\begin{aligned} E_{\text{TOT}} = & (u_i + u_{\text{ii}}) \left\{ \frac{1}{1-\beta} \left(\frac{1}{1-a} - f \right) \right\} m + u_{\text{iii}} \left(\frac{1}{1-a} - f \right) m + u_{\text{iv}} \left(\frac{1}{1-a} \right) m \\ & + u_v m + u_{\text{vi}} m + (u_b + u_c) fm \end{aligned} \quad (11)$$

4.4. Consumption of ancillary materials and production of air, waterborne and solid wastes

Eq. (11) holds also for the consumption Q_{TOTi} of each ancillary material required, the only difference being that, instead of u_j , we have q_j , i.e. the specific mass. The latter is defined as the mass of the required ancillary materials (or air, waterborne and solid waste produced) per unit mass, and instead of E_j , we have Q_{ji} .

5. Field data

5.1. Data for energy consumption

For the inventory analysis of the reverse supply chain of the used batteries we assume that the electricity consumed is supplied from the distribution network of the public power corporation (PPC), the liquid fuels from Greek refineries, while the rest of the fuels, except lignite, originate from imports. The electricity production in Greece is mainly based on thermal power generation (about 90%) using lignite as fuel in most cases (Boustead and Hancock, 1994; CEC, 1991b,c, 1992; Livas, 1994).

The total values for airborne emissions as well as the total energy consumption for the supply of 1 MW h of electricity to the end user are summarized below (Georkakelos, 1996).

Energy consumption (MJ/MW h)	13 122
SO ₂ production (kg/MW h)	5.416
NO _x production (kg/MW h)	1.811
Participates production (kg/MW h)	0.690
CO ₂ production (ton/MW h)	1.533

5.2. Data for transportation–distribution

Transportation and distribution are processes, which take place at any stage of the system, in relation to either the main supply chain or the reverse supply chain, which is examined in this study.

In this study, four types of vehicles are distinguished (light and heavy-duty vehicles which use diesel or gasoline as fuel) and three types of roads (urban, rural and highway) have been taken into consideration.

The calculation of energy consumed as well as air emissions produced is limited to the above vehicle types while they are in operation, and not during maintenance and repair (Fig. 8). We also ignore the emissions that are produced when vehicles start to operate with cold engine (cold start emissions) or the emissions of all the volatile organic compounds (VOC) evaporated daily due to the temperature difference between gasoline tank and the environment (diurnal emissions). Furthermore we ignore the emissions, which are also produced when the engine turns off (hot soak

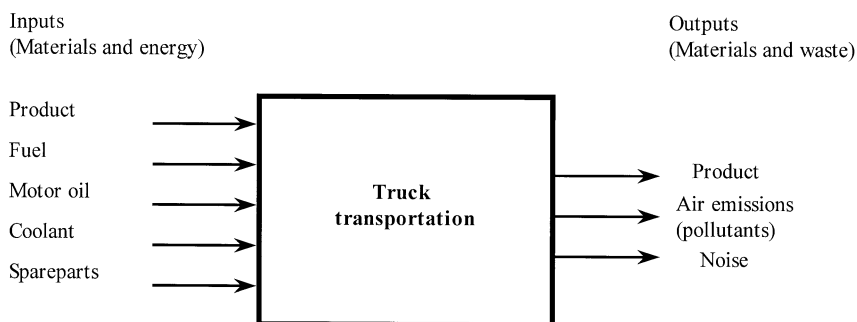


Fig. 8. A typical distribution and transportation process with trucks.

emissions), and the running losses as a result of vapor generated in gasoline tanks during vehicle operation.

For this study the following parameters have been taken into consideration for accounting the emissions when the engine is in operation (hot emissions) (CEC, 1991a):

- total annual kilometers driven per vehicle,
- share of kilometers driven under the driving modes ‘urban’, ‘rural’ and ‘highway’,
- average speed of the vehicles driven under the driving modes ‘urban’, ‘rural’ and ‘highway’,
- speed-dependent hot emissions factors.

From the above the results of Tables I–IV in [Appendix A](#) are obtained, which allow to account the total energy consumption and the total air emissions during the transportation either during the collection or the distribution stage.

Regarding sea transportation of the imported quantity of batteries and some ancillary materials (e.g. soda) or of grids of secondary lead to the end users, the variation of vessel sizes is high starting from small motorships of 20 000 tons and up to supertankers of 250 000 tons ([Georgakelos, 1998](#)). Table V of [Appendix A](#) shows the differences in energy performance and the required energy for the transportation. The latter consists of the relative fuel consumption for the operation of ships and of the energy for their constructions and maintenance. This last portion of energy concerns about 12% of the required energy in fuels.

5.3. Data for the inventory analysis

Additional data, some of which are used in the inventory tables, are mentioned below. This data concerns mainly solid wastes and liquid effluents.

The main solid material wastes associated with the production of secondary lead are ([Barry et al., 1993](#)):

- slag, mattes and drosses removed during the disaggregation and formation stages,
- dust recovered from dry air pollution control equipment,

- solids generated during the preparation of secondary feedstocks,
- sludge as a result of liquid effluents.

The main liquid effluents arising during the production of secondary lead are (Barry et al., 1993):

- wet air pollution control;
- cooling water;
- surface runoff concerning the liquid effluents during cleaning, maintenance and machines operation.

5.4. Collection (I)/transportation (II)

In modeling of the batteries reverse supply chain, collection and transportation are examined separately, but in fact, they are considered as one stage. It should be noted that data concerning the collection stage are hardly available. More specifically, it is very difficult to make measurements concerning the collection procedure of batteries, especially when they are imported from a country outside the European Union (imports concern about 60% of the used batteries). The state before being imported, the special characteristics of the product, the rate and mode of collection make the gathering of reliable data for this procedure impossible.

On the other hand, data for the transportation stage concerns information about the movement of raw materials, that is, used batteries from collection points (electrician shops, material recovery facilities, landfills, etc.) to processing units (recycling units).

For this stage, we also examine the transportation of ancillary materials. Using the results of Tables I, II, III, IV and V of [Appendix A](#) and defining ‘distance’ as the average distance which the transportation means cover for each network we calculate the energy consumed and the produced emissions.

5.5. Disaggregation (III)

The main processes taking place at this stage is disaggregation (breaking and separation) of different materials of batteries. Several operations related to disaggregation may generate liquid effluents. These include battery acid, water for cooling for battery breakers, such as saws and hammers, and wash-down waters. These effluents are likely to be characterized by the presence of metals and be acidic in nature (Barry et al., 1993).

The solids generated during battery disaggregation, which include metallic lead, lead paste, spent acid, hard rubber, polypropylene etc. are treated as potentially valuable products (e.g. plastic, which may be recycled and reused in other products). Paper is disposed in landfills.

After the separation of the batteries’ materials, storage of lead (PbSO_4 , PbO_x and metallic Pb) takes place. Some quantity of lead may escape in the ecosystem.

5.6. *Remanufacturing/processing/formation (IV)*

The processes taking part at this stage concern mainly the recovery of lead (hard lead) through pyrometallurgical production processes, the separation of antimony from production of soft lead and the air pollution control system.

Liquid effluents are generated during refining of air emitted by the pollution control systems, surface runoffs and cooling.

The main solid wastes generated are slag associated with smelting operations, the dust collected by the air pollution control system and solids generated during the preparation of secondary feedstocks. The quantity and composition of the solid waste generated in this type of facility is very much dependent upon the nature of the feedstock (used batteries) supplied to the processing and production stage, the processes used in the production and the final product (lead quality) obtained.

5.7. *Supply of the ancillary materials (α)*

At this stage no processing of ancillary materials takes place. The data gathered concern the quantity of these materials needed for the recovery of the metallic lead at the processing stage.

5.8. *Transportation/distribution (V)*

The transportation at this stage includes the movement of the final products (grids of lead) from the processing unit to the storage facility and, finally, to the end user.

Similarly to the transportation of used batteries from the collection points, the average distance covered by the final products to reach the end user is used.

6. Disposal

Disposal of used batteries concerns an alternative channel or end-of-life scenario that a used battery may go through if it is not collected at the different storage points (car electrician's shops or wholesale collection points) and then transported to the recycling units. Disposal comprises two basic life cycle stages, namely collection including transportation and landfilling or dumping. Dumping of used batteries is not a usual practice. As mentioned above, over 90% of the used batteries are recycled in order to recover lead, which is the most valuable component contained.

The results of the analysis referring to disposal of used batteries presented in the sequel are based on the following assumptions:

- 1) the functional unit is 1 ton of lead (i.e. the same as in the case of recovery);
- 2) used batteries disposed are of the same quality as that of used batteries recovered. Additionally, used batteries imported would also be disposed in the country of origin;

- 3) collection and transportation of used batteries for disposal take place in a similar way as in the recovery case.

Similar to reverse supply chain, data concerning collection of used batteries are not available or it is assumed that environmental impacts are negligible. So, we concentrated on data gathering for the transportation stage. This data concerns movement of used batteries from collection points (electrician shops, material recovery facilities, etc.) to landfills (Table 2).

The environmental impact categories, which are mostly influenced from the disposal of the used batteries, are solid wastes and liquid effluents during landfilling and airborne emissions created during transportation of the used batteries to landfills. In particular:

- 1) the main solid material wastes associated with batteries disposal are hazardous waste due to high toxicity of lead either metallic (Pb) or paste form (PbSO_4 , PbO_x) and bulk wastes as a result of the remaining components (plastics, paper, etc.) after the use of batteries;
- 2) the main liquid effluents resulting from batteries disposal are acid and water, which are the remaining effluents of the oxidation reduction during charging and discharging of batteries;
- 3) the main airborne emissions resulting from batteries disposal are usual airborne emissions, which result during the transportation of used batteries to landfills with garbage collection trucks.

Finally, all the inputs and outputs of the system concerning mass or energy are listed in the Inventory Table of disposal (Table 3).

7. Conclusions

The reverse supply chain aiming at the recovery of SLI or lead–acid batteries from used batteries in Greece has been presented in this paper. A model formulation adapted to reverse supply chains is proposed in order to be used as a tool for listing all the environmental exchanges appearing in similar product systems. Focusing on lead recovery in a country that environmental regulations are less strict than in other countries, inventory data are provided in order to be compared either with similar product systems, which use different technology, or to alternative end-of-life scenarios. Additionally, these data could be useful in case of LCIA studies where critical environmental and health impacts associated with lead recovery could be addressed. It is also noted that not only the lead emissions but also all the environmental exchanges associated with lead recovery processing from used batteries are examined and listed.

The task of listing and determining all the environmental impacts associated with this chain has been possible with the help of LCIA. Thus, based on several

Table 2
Data sources—data references

Data reference									
Product system and process type	Data specificity			Data source type					Comments
	Product specific	Site specific	General	1	2	3	4	5	
<i>Collection</i>									
Road transportation of used batteries			✓			✓		✓	Literature (CEC, 1991a)
Sea transportation of used batteries			✓			✓		✓	(Georgakelos, 1998)
Transportation of ancillary materials			✓					✓	Literature (CEC, 1991a)
<i>Disaggregation</i>									
Separation		✓			✓				Direct measurements
<i>Remanufacturing/Processing/Formation</i>									
Furnace		✓				✓			Empirical estimation
Cleaning basin		✓				✓			Empirical estimation
Air control system			✓			✓			Empirical estimation
<i>Distribution</i>									
Road transportation of lead grids			✓			✓		✓	Estimation–Literature (CEC, 1991a)
Sea transportation of lead grids			✓			✓		✓	Estimation–Literature (Georgakelos, 1998)
Internal distributions			✓					✓	Estimation–Literature (CEC, 1991a)

1, Measurements; 2, computations (e.g. mass balance, input data, etc.); 3, extrapolation of data from similar process type or technology; 4, extrapolation of data from different process type or technology; 5, estimate. Product-specific data: concern specific processes of batteries' reverse chain. Site-specific data: concern data from actual sites in the product system of batteries' reverse chain. General data: all the others.

Table 3
Comparative results between reverse supply chain and disposal of batteries

Inventory tables of batteries' reverse chain						Inventory table of disposal chain			
		Collection	Disaggregation	Remanufacturing	Distribution	Total			Total
<i>Power demands</i>									
Electrical energy	kWh		57.14	64.36		121.50	Electrical energy	kWh	0.30
Liquid fuels (oil, etc.)	MJ	78.36		5639.30	230.20	5847.85	Liquid fuels (oil, etc.)	MJ	100.63
Other fuels						0.00	Other fuels		0.00
<i>Resource consumption</i>									
Carbon (C)	kg			142.86		142.68	Carbon (C)	kg	0.00
Oil	kg	1.68		119.00	4.95	125.63	Oil	kg	2.16
Water	m ²		0.53			0.50	Water	m ²	0.00
Iron (Fe)	kg			171.43		171.43	Iron (Fe)	kg	0.00
Antimony (Sb)	kg			−7.14		−7.14	Antimony (Sb)	kg	7.14
Lead (Pb)	kg					0.00	Lead (Pb)	kg	1000.00
Copper (Cu)	kg			−1.20		−1.20	Copper (Cu)	kg	1.20
Sodium chloride (NaCl)	kg			71.43		71.43	Sodium chloride (NaCl)	kg	0.00
Sodium carbonate (Na ₂ CO ₃)	kg			142.86		142.86	Sodium carbonate (Na ₂ CO ₃)	kg	0.00
Sodium hydroxide (NaOH)	kg			1.60		1.60	Sodium hydroxide (NaOH)	kg	0.00
Calcium oxide (CaO)	kg		9.52			9.52	Calcium oxide (CaO)	kg	0.00
Sulfate (S)	kg			0.80		0.80	Sulfate (S)	kg	0.00
Sodium nitrate (NaNO ₃)	kg			0.80		0.80	Sodium nitrate (NaNO ₃)	kg	0.00
<i>Airborne emissions</i>									
Carbon dioxide (CO ₂)	kg	5.50	24.10	27.43	1.70	58.73	Carbon dioxide (CO ₂)	kg	0.00
Carbon monoxide (CO)	g	88.23		87.14	352.33	557.67	Carbon monoxide (CO)	g	179.00
HC	g	0.00			0.00	0.00	HC	g	0.00
HCHO	g	0.00			0.00	0.00	HCHO	g	0.00
Sulfate dioxide (SO ₂)	g	0.01	84.85	969.10	0.00	1053.96	Sulfate dioxide (SO ₂)	g	0.00
Nitrogen oxides (NO _x)	g	74.35	28.40	162.70	194.83	460.25	Nitrogen oxides (NO _x)	g	82.86
Particulates	g	7.33	10.51	606.12	20.87	645.13	Particulates	g	9.00
Volatile organic compounds (VOC)	g	26.72			63.20	89.92	Volatile organic compounds (VOC)	g	26.20

Table 3 (Continued)

Inventory tables of batteries' reverse chain						Inventory table of disposal chain			
		Collection	Disaggregation	Remanufacturing	Distribution	Total		Total	
Lead (Pb)	g			349.40		349.40	Lead (Pb)	g	0.00
<i>Liquid effluents</i>									
Acid (H ₂ SO ₄)	g					0.00	Acid (H ₂ SO ₄)	kg	571.43
Lead (Pb)	g					0.00	Lead (Pb)	g	0.00
<i>Solid wastes</i>									
Bulk waste (plastic and paper)	kg		452.63			452.63	Bulk waste	kg	452.60
Slag and ashes	kg			1484.30		1484.30	Slag and ashes	kg	0.00
Hazardous waste (Lead (Pb))	kg		33.93			33.33	Hazardous waste	kg	1833.14

assumptions, an inventory analysis referring to the above chain has been conducted whose results have been summarized in an Inventory Table (Table 3).

Additionally, a comparison between the respective logistics channels of disposal and recovery of used batteries referring to their environmental impact has been performed. In particular, all significant environmental loads from each channel have been measured in order to investigate the environmental performance of lead's recovery.

The Inventory Table (Table 3), in both cases, shows which substances are exchanged with the surroundings by the processes associated with the waste management chains examined, and it provides an overview of where the large quantities occur. The exchanges have been summarized in power demands, resources consumption, and emissions to air, water and soil as waste, and in impacts on the working environment, which have been quantified in terms of time per product, for which the impact has been assessed to last.

Examining each category of environmental exchanges separately, the following results have been gathered in the Inventory Table (Table 3) of the lead recovery and disposal of batteries channels and some preliminary conclusions can be drawn:

7.1. Resources consumption

For the production of one ton of secondary lead about 2.86 tons of used (SO) batteries are needed to enter the recycling unit. As shown in the Inventory Table (Table 3), a quantity of 1.271 tons of natural resources is consumed in order for the predefined quantity of lead to be recovered. At least 0.541 tons of this quantity are accounted as pure metals content in the ores. About 0.229 tons of resources concern fuels for the energy consumed in lead-processing facilities and transportation means, and therefore, do not enter into the secondary lead. Finally, 0.5 tons or 39% of the sum of resources consumption concern water demands of the examined product system that is discarded as liquid effluent.

As it is expected, resources consumption (excluding fuels consumption) takes place within lead-processing facilities. The quantity of fuels, which are consumed at the life cycle stage of remanufacturing, is also remarkable. This quantity corresponds to 0.119 tons or 52% of the total quantity of fuels consumed.

The negative figures shown in the Inventory Table (Table 3) concern the remanufacturing life cycle stage. This is attributable to the fact that some metals except lead are recovered during batteries recycling.

Regarding the disposal chain of batteries, the only inventoried resources consumption concern fuels needed for the transportation of the collected used batteries to landfills. However, the quantity of lead that is not recycled is assumed to be resource consumption in the disposal chain. The quantity of lead lost is, therefore, estimated to be about 1 ton. By comparing the examined waste management policies in this environmental category, one can see that resources consumption in reverse supply chain is equal to 66.3% of the respective consumption in the disposal chain as a result of the above assumption.

Considerable power demand is connected with the reverse supply chain of used batteries, especially within the recycling unit, either in electrical energy or in liquid fuels consumed. However, all power demand in the disposal chain is associated with the energy produced as a result of fuels consumption.

7.2. Airborne emissions

The emissions to air are derived mainly from the energy systems. This means that they are emitted as a result of the electrical energy needed for the operation of lead-processing facilities (life cycle stages of disaggregation and remanufacturing). Regarding emissions released by the use of transportation means (Fig. 9), it is clear that there is a large difference between them and emissions from the plants of the recycling unit (lead, nitrogen oxides and sulfate dioxide).

From Fig. 10, the large contribution to atmospheric pollution by the reverse supply chain against the disposal chain of batteries is evident. This is attributable to the fact that the disposal chain activities do not consume electrical energy as long as no processing of used batteries coming to landfills takes place. The emissions to air come mainly from the use of transportation means (garbage trucks 3.5–16 tonnes).

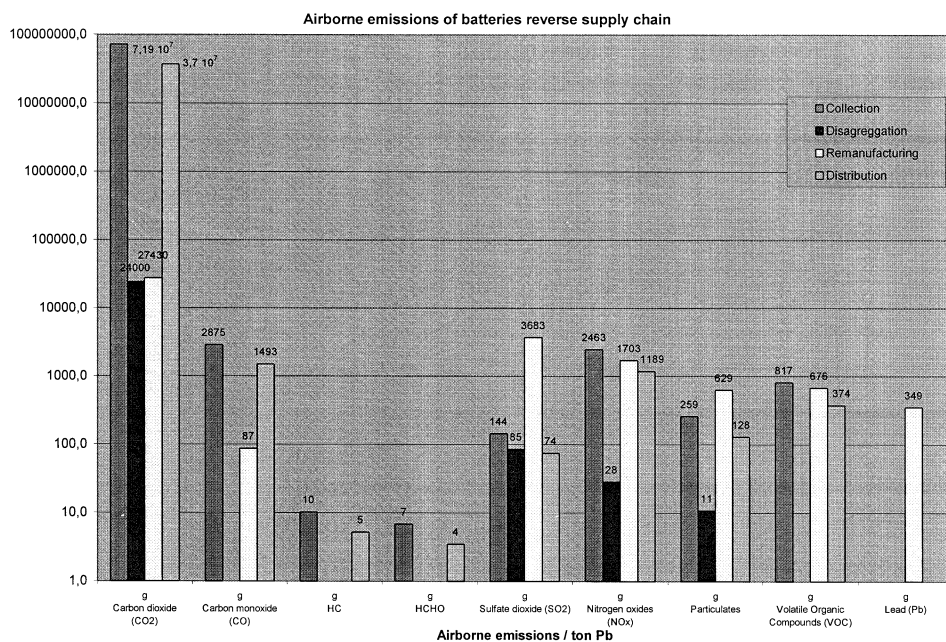


Fig. 9. Airborne emissions of batteries reverse supply chain.

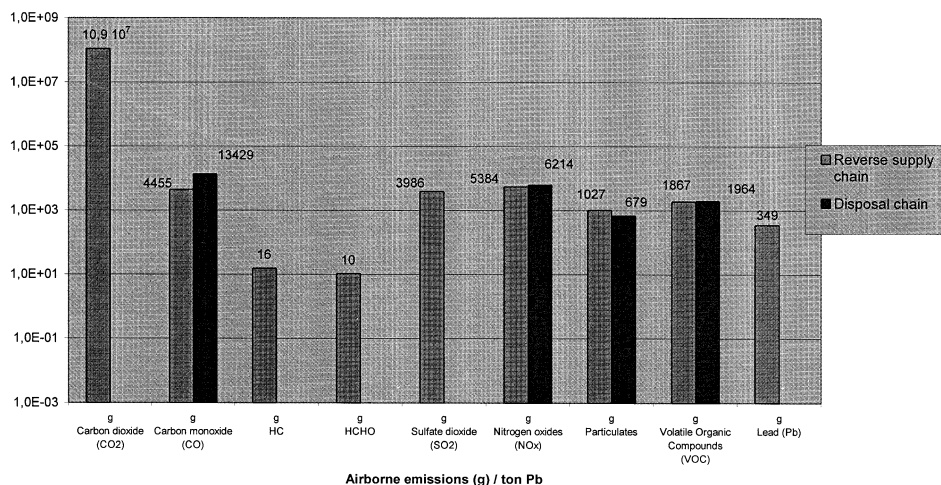


Fig. 10. Disposal vs. reverse supply chain airborne emissions.

7.3. Liquid effluents

Considerable quantities of liquid effluents are produced only in the disposal channel. These effluents concern mainly acid dilutions, which is contained in used batteries. On the other side, liquid effluents are not detected in the recovery chain, because a large portion of the imported batteries have been emptied of such dilution, while the dilution of batteries supplied domestically are neutralized during the disaggregation stage. The neutralized liquid effluents are not directed to a drainage system, instead they are evaporated.

7.4. Solid wastes

The largest quantity of solid wastes concerning the reverse supply chain of batteries arises from the remanufacturing life cycle stage, namely 1.484 tons of slag and ashes. Slag is derived as a result of chemical reactions taking place within lead-processing facilities such as the re-melting process in rotary furnace (antimonial lead). Ashes come from the combustion of the mixture of lead paste and ancillary materials. They are collected from the baghouse of the electrostatic filter installed in air control system. A smaller quantity of solid wastes of 0.486 tons is derived in the disaggregation life cycle stage. These concern about 0.453 tons of bulk waste and consist of plastics separators, grips, case, paper and rubber. This quantity may be smaller if more plastics are forwarded for recycling. The rest 0.333 tons include hazardous waste mainly from the metallic lead in the form of small particles.

Regarding the disposal chain of batteries, the quantity of the solid wastes increases dramatically, because of the lead that is not recycled. The quantity of slag and ashes as remains of lead-processing facilities is equal to zero.

The main difference between the two channels concerns the quantity of lead in the form of hazardous waste in the disposal chain, which is connected with the well-known hazards against human health and nature. On the other side, in the recovery chain, nearly all the quantity of lead contained in used batteries is recovered, thus avoiding extraction of this quantity from the earth. One more difference is located in the environmental category of slag and ashes that are derived mainly in the reverse supply chain of batteries as a result of the re-melting process (Fig. 11).

7.5. Impacts on the working environment

It is noted that the issue of impacts on the working environment for both reverse supply and disposal chain of batteries have not been addressed. This is due to the fact that data concerning the working environment have not been inventoried as well as that data from the reference product system or its parts have not been used.

With the help of Inventory Analysis, apart from the computation and data listing concerning predefined data categories, one more important task is also accomplished. This concerns identification of the most significant sources of resources consumption as well as their potential impacts. Additionally, the logistics activities

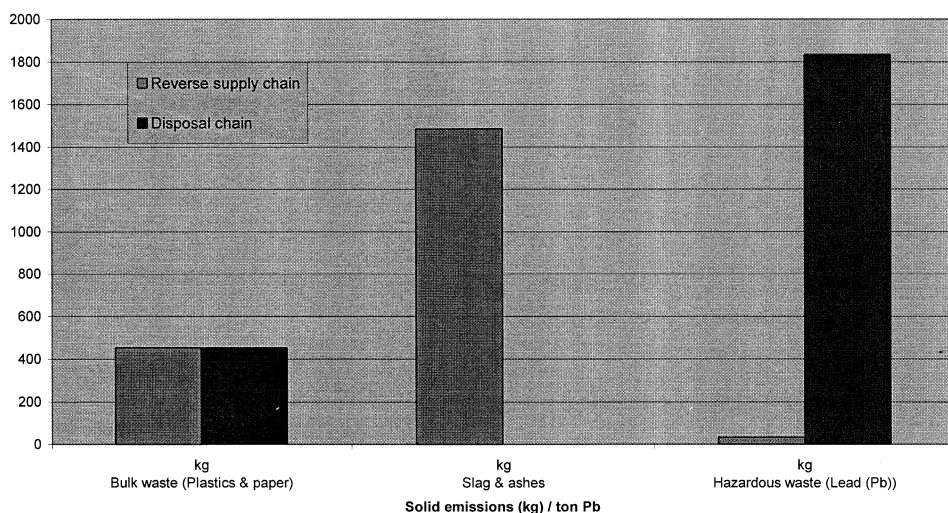


Fig. 11. Reverse supply chain vs. disposal chain solid wastes.

that contribute mostly to the environmental degradation and could need extended investigation (e.g. processing of hazardous waste in landfills, environmentally sound technology of re-melting processes, etc.) are identified.

Finally, by studying the results arising from the inventory analysis, it is clear that reverse supply chain gives environmentally better results regarding resources consumption, liquid effluents and solid wastes. On the other hand, the disposal chain is better in power demands and airborne emissions. However, the superiority of one chain over the other regarding some environmental categories does not show which of them has the least aggregate contribution to the environmental degradation. Additionally, the large quantities of substances that are released in each end-of-life scenario do not mean that the substances have a considerable contribution to environmental impacts. This is explained by the fact that different substances, among others, possess different hazard properties (e.g. toxicity of lead against sulfuric acid).

Appendix A

Table I:
Emission factors for diesel light duty vehicles < 3.5 tonns (CEC, 1991a).

	Co (g/km)	No _x (g/km)	VOC (g/km)	Par-ticulates (g/km)	Consumption (g/km)
Urban	2.00	1.60	0.40	0.25	106.25
Rural	0.80	1.20	0.25	0.25	68.00
Highway	060	1.25	0.13	0.16	63.75

Table II:
Emission factors for gasoline light duty vehicles < 3.5 tonns (CEC, 1991a).

	Co (g/km)	No _x (g/km)	VOC (g/km)	Particulates (g/km)	Consumption (g/km)
Urban	30.00	3.00	3.60	–	120.00
Rural	15.00	2.70	1.70	–	67.50
Highway	12.00	3.20	1.00	63.75	–

Table III:

Emission factors for heavy duty diesel vehicles 3.5–16 tonns (CEC, 1991a)

	Co (g/kg) fuel (g/km)	No _x (g/kg) fuel (g/km)	VOC (g/kg) fuel (g/km)	Particulates (g/kg) fuel (g/ km)	Consumption 1/100 (km) (g/km)
Urban	82.8 [18.8]	38.5 [8.7]	12 [2.75]	4.3 [0.95]	27.5 [227]
Rural	38.6 [7.3]	39.1 [7.4]	4 [0.76]	4.3 [0.82]	22.9 [189]
Highway	27.1 [0.66]	38.9 [6.0]	4 [0.6]	4.3 [0.66]	18.7 [154]

Table IV:

Emission factors for heavy duty diesel vehicles > 16 tonns (CEC, 1991a).

	Co (g/kg) fuel (g/km)	No _x (g/kg) fuel (g/km)	VOC (g/kg) fuel (g/km)	Particulates (g/kg) fuel (g/km)	Consumption 1/100 (km) (g/km)
Urban	51.4 [18.8]	44.2 [16.2]	16 [5.8]	4.3 [1.6]	44.4 [366]
Rural	22.2 [7.3]	45.2 [14.8]	8 [2.6]	4.3 [1.4]	39.7 [328]
Highway	14.2 [4.2]	45.8 [13.5]	8 [2.3]	4.3 [1.25]	35.6 [294]

Table V:

Total required sea transportation energy in relation to vessel size (Georgakelos, 1998)

20	0.208	0.233
30	0.190	0.213
40	0.170	0.190
50	0.152	0.170
60	0.1370	0.153
70	0.125	0.140
80	0.115	0.129

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